Thermal Monitoring of Geological Changes During Excavation

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13. ABSTRACT

The objective of this program is to determine the feasibility of using measurements of local temperature distributions along the walls of an excavation as an aid in predicting hazards to tunneling operations. These hazards include joints, unconsolidated regions, gas and other geological discontinuities. The principle geolcgic medium of interest is "hard rock."

The goal of the first two quarters was to gather information pertaining to possible temperature conditions, rock formations and general mining environmental conditions as well as information about the state of the art in non-contact temperature measuring devices. The Colorado School of Mines' experimental mine was visited for the purpose of evaluating the mine as a possible site for actual temperature measurements. Contact was established with Barnes and technical discussions initiated concerning the performance and possible improvement of sensitivity, portability and safety requirements for instruments to be used in mines.

Calculations were performed on theoretical models of temperature fields around geologically different areas in an otherwise homogeneous rock matrix, and numerical data were obtained which are pertinent for the design of the radiometer.

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SECTION 1

TECHNICAL REPORT SUMMARY

The objective of this program is to determine the feasibility of using measurements of local temperature distributions along the walls of an excavation as an aid in predicting hazards to tunneling operations. These hazards include joints, unconsolidated regions, gas and other geological discontinuities. The principle geologic medium of interest is "hard rock."

The goal of the first two quarters was to gather information pertaining to possible temperature conditions, rock formations and general mining environmental conditions as well as information about the state of the art in non-contact temperature measuring devices. The Colorado School of Mines' experimental mine was visited for the purpose of evaluating the mine as a possible site for actual temperature measurements. Contact was established with Barnes and technical discussions initiated concerning the performance and possible improvement of sensitivity, portability and safety requirements for instruments to be used in mines.

Calculations were performed on theoretical models of temperature fields around geologically different areas in an otherwise homogeneous rock matrix, and numerical data were obtained which are pertinent for the design of the radiometer.

The temperature fields around some simplified models of geothermal sources were mathematically analyzed. The investigation here follows very closely that by Rakiti. The Conference on the Underground Mining Environment at Rolla, Missouri, was attended at Bendix expense. Here we had the opportunity to observe the environment in a local lead mine. The Barnes radiometer was delivered to us but laboratory tests showed that the instrument was not stable in the temperature range in which we have to work. The instrument was returned to the vendor for repair.

SECTION 2

INTRODUCTION

Voids, watercourses, drastic changes in mechanical strength of the rocks due to unconsolidated regions, geothermal sources, gas pockets, or gas seepages all present hazards for men and equipment involved in tunneling through rock. The early detection of such geological changes in a tunneling operation is thus of great importance. New technical areas are being explored as to their applicability to the above mentioned problems.

All of the hazardous geological changes mentioned have one physical property in common, namely that, in the affected region, the thermal conductivity is different from that in the undisturbed rock formation. In the cases of gas seepage or geothermal sources, the "obstacles" represent thermal heat sinks or thermal heat sources into which heat flows or from which heat emerges. All of these disturbances mentioned will lead to a distortion of the natural temperature field created by the steady heat flow from the interior of the earth to the surface. Since in truly undisturbed rock the isotherms are lines parallel to the flat earth surface (highly idealized), the monitoring of the rock temperature of the tunnel walls during excavation should then by temperature change indicate and predict any change in the geological formation. This, however, is only true if no other thermal disturbances are present which change those tunnel wall temperatures in an uncontrolled manner. A preliminary study showed that the temperature changes to be expected from geological changes such as voids, faults, dykes and water courses of ambient temperatures would only create very small changes (on the order of 10^{-3} °C) which require a most sensitive, noncontacting, portable temperature measuring device. The instrument best fulfilling these requirements turned out to be the Barnes II-512 radiometer.

From the study of literature about excavating, tunneling, and mining, it became obvious that the temperatures of tunnel walls are influenced by such factors as location, ventilation, humidity, and even wall roughness. Therefore, the emphasis of the program was placed on the study of papers dealing with underground temperature measurements, on theoretical mathematical investigations of temperature distributions of several "obstacle" models, and on the experimental investigation of the mine environment.

SECTION 3

LITERATURE STUDIES

A thorough study of tables and papers was performed to obtain both values of thermal conductivities of pure minerals as well as rocks consisting of more or less homogeneous mixtures of such minerals. Two important fact seemed to emerge from this search, namely that in materials with the same mineralogical names there was always a certain spread in values depending on the location from which they came and also to a somewhat lesser degree on the investigator. Even in areas where there was merely one type of rock formation, the measured thermal conductivities of samples varied sometimes by as much as a factor of 1.5. It seems, however, that for hard rocks, the thermal conductivity ranges from 5 to 16 x 10^{-3} cal/cm sec °C. The importance of this range for the thermal conductivity will be discussed with the theoretical model described later.

Another area of interest is the magnitude of thermal gradients to be encountered in underground tunnels. Over the USA, one finds the range of thermal gradients:

Minimum:	New Mexico	- 8.0 x 10^{-3} °C/m
Maximum:	Eureka, Utah	- 80.0 x 10^{-3} °C/m
USA Average:		- 20 x 10^{-3} °C/m

The highest thermal gradients seem to occur in areas where many geothermal sources are known to exist. If these thermal gradients do not change rapidly from location to location within the tunnel, then the high values can be useful for the detection of geological changes.

Another area of literature search, namely the search for information on the effects of the tunnel environment on the detectable thermal gradient of the tunnel walls, yielded very few results. It is to be expected that the tunnel ventilation combined with possible humidity and the existence of a fractured layer on the tunnel walls will lead to local cooling or even heating, which, if occurring in an uncontrolled manner, will be a perturbation on the tunnel wall temperature measurements. The size of these regions - if they exist - and their temperature deviation from the undisturbed case must be known, especially their magnitude, since they could possibly obscure the sought-after temperature completely.

Because of the importance of the disturbing factors and the apparent nonexistence of such data, we decided to perform such measurements in the first part of the field measurements to be made in the Colorado School of Mines' Experimental Mine.

Another area of literature search was aimed at papers treating the disturbance of the "natural" temperature field of the earth by various types of geological inhomogeneities. The cases dealing with the mere difference of thermal conductivity are well known and are part of standard textbooks on mathematics of heat flow. The ones dealing with geothermal sources are of a more complicated nature and only a few very special cases which do not directly apply to our problem could be found. However, these papers are an important basis for further mathematical analysis.

SECTION 4

MATHEMATICAL MODELS

Two models will be considered:

(1) A spherical object with different thermal conductivity.

(2) A cylindrical object of infinite length with a different thermal conductivity.

Model 1 - The temperature measurements have to be performed on tunnel walls, thus leading to the geometrical setup pictured in Figure 4-1. The temperature field around the obstacle of radius a is given by equation (1).

$$T = T_c + Gb_I + Gb_I \left(\frac{\kappa - \kappa_1}{2\kappa + \kappa_1}\right)\left(\frac{a^3}{r^3}\right)$$

This simple means that a pertubation $G\, b_I \left(\frac{\kappa - \kappa_1}{2\kappa + \kappa_1}\right) \left(\frac{a^3}{r^3}\right)$ is added to the undisturbed temperature field. Thus the required accuracy in the temperature measurement is determined by the size of this term. In equation (1),

T = Actual temperature measured.

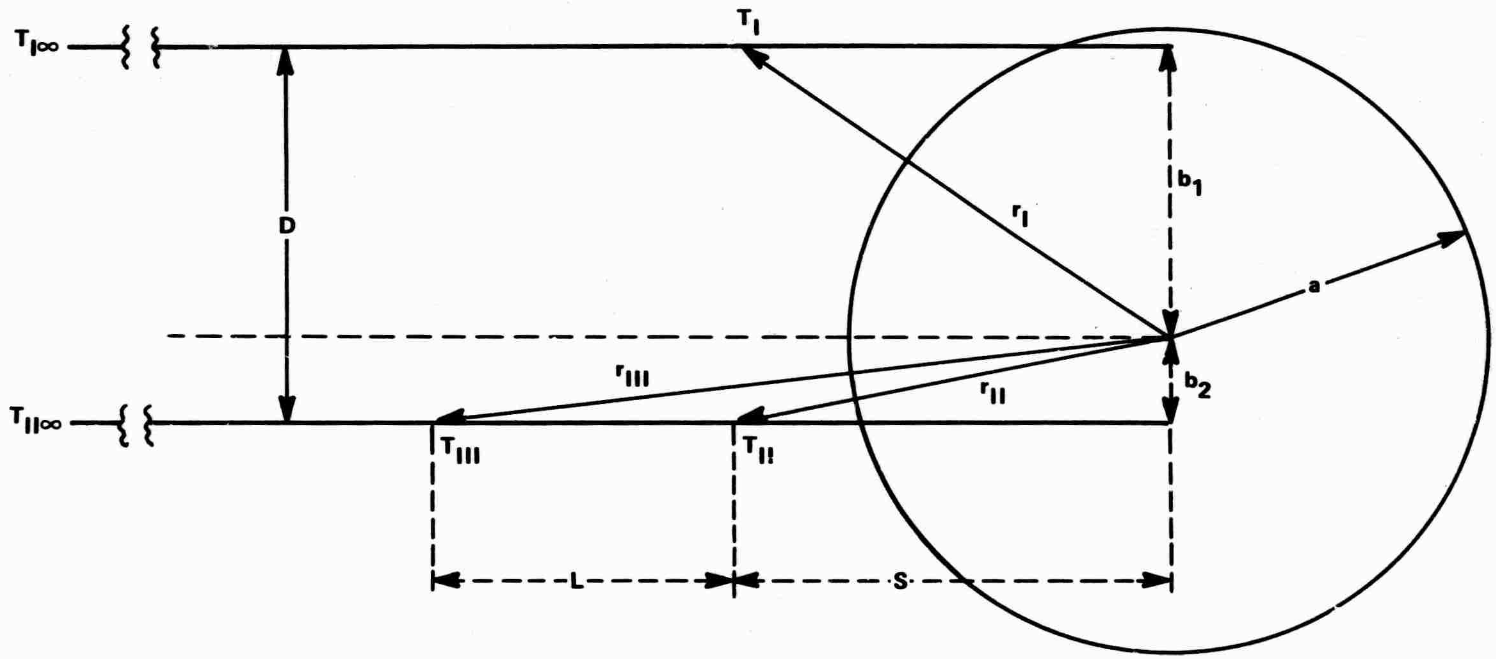
T_c = Temperature at a level defined by the center of the obstacle but in an undisturbed field.

G = Temperature gradient in the undisturbed field.

κ; κ_1 = Thermal conductivities of the rock material and obstacle respectively.

The first example to be discussed is that of a simple void cavity which means that approximately

$$\kappa >> \kappa_1$$



D = DIAMETER OF MINE SHAFT

a = RADIUS OF "OBSTACLE"

$T_I; T_{II}; T_{III}$ = MEASURED TEMPERATURES

$r_I; r_{II}; r_{III}$ = DISTANCE OF LOCATIONS OF T FROM CENTER OF OBSTACLE

$b_1; b_2$ = ECCENTRICITY OF TEMPERATURE LOCATIONS

$T_{I\infty}; T_{II\infty}$ = UNDISTURBED TEMPERATURES

S = DISTANCE OF PLANE $T_I; T_{II}$ FROM CENTER OF OBSTACLE

L = DISTANCE BETWEEN $T_I; T_{II}$ AND T_{III}

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Figure 4-1 - Geometrical Layout of Tunnel, Obstacle and Temperature Measuring Points

Table 4-1 - Detectable Temperature Difference as a Function of Distance from Spherical Obstacle

ΔT for $\kappa_1 >> \kappa$	ΔT for $\kappa_1 << \kappa$	Obstacle Wall Thickness
5.4×10^{-2}	2.7×10^{-2}	0% of cavity radius
1.6×10^{-2}	0.8×10^{-2}	50%
3.64×10^{-2}	1.82×10^{-2}	20%
4.06×10^{-2}	2.03×10^{-2}	10%
1.32×10^{-2}	0.66×10^{-2}	60%
1.1×10^{-2}	0.55×10^{-2}	70%
0.92×10^{-2}	0.46×10^{-2}	80%
0.788×10^{-2}	0.394×10^{-2}	90%
0.676×10^{-2}	0.338×10^{-2}	100%

According to this table, the temperature signal will be down to the detection limit of the radiometer.

For a cylindrical obstacle, the equation of temperature is

$$\Delta T = G\, b\, \frac{\kappa_1 - \kappa}{\kappa_1 + \kappa} \left(\frac{a^2}{r^2} \right)$$

The results for this case are shown in Table 4-2. Here, ΔT is the same for $\kappa_1 > \kappa$ and $\kappa > \kappa_1$.

Table 4-2 - Detectable Temperature Difference as a Function of Distance From Obstacle (Cylindrical Obstacle)

ΔT	Wall Thickness
2.7×10^{-2}	0%
2.23×10^{-2}	10%
1.88×10^{-2}	20%
1.60×10^{-2}	30%
1.38×10^{-2}	40%
1.20×10^{-2}	50%
1.055×10^{-2}	60%
0.935×10^{-2}	70%
0.835×10^{-2}	80%
0.75×10^{-2}	90%
0.675×10^{-2}	100%
0.612×10^{-2}	110%
0.56×10^{-2}	120%
0.51×10^{-2}	130%
0.47×10^{-2}	140%

Since we have used two extreme cases $\kappa \gg \kappa_1$ and $\kappa \ll \kappa_1$, the real values encountered in actual measurements are somewhere between these numbers. If one assumes that for instance granite and quartz occur together, then with

$$\kappa \approx 7 \times 10^{-3} \text{ cal cm sec °C} \quad \text{- Quartzite}$$

$$\kappa_1 \approx 10 \times 10^{-3} \text{ cal cm sec °C} \quad \text{- Granite}$$

$$\frac{\kappa_1 - \kappa}{\kappa_1 + \kappa} = 0.1765 \quad \text{and} \quad \frac{\kappa - \kappa_1}{2\kappa + \kappa_1} = 0.111$$

This means that the T measured for this occurence would be even smaller by one order of magnitude. This would under even ideal environmental conditiona make the measurements extremely difficult with existing equipment.

In addition to the radiometer sensitivity required, the effects of the "mine environment" must also be considered. The ventilation system adds in an uncontrolled fashion cooling mechanisms, the effects of which are expected to be much larger than the perturbation ΔT. There is evidence of this from the measurements and investigations performed by Merril on loose rock, and the observations made with an infrared viewer at the Mining Conference at Rolla, Missouri, where temperature variations of 0.1°C could be observed over small spacial regions. The situation can be different in those cases where the obstacle is a heat source or a heat sink.

Concerning the mathematical models analyzed, one must bear in mind that all one can measure in the tunnel is temperatures and then determine from these the location of the obstacle and if possible its dimension.*

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*The equations to be solved are:

$$\frac{T_I - T_{I\infty}}{G} = \frac{b_1 A^3}{(S^2 + b_1^2)^{3/2}}$$

$$\frac{T_{II} - T_{I\infty} + G D}{G} = \frac{(b_1 - D) A^3}{(S^2 + (b_1 - D)^2)^{3/2}}$$

$$\frac{T_{II} - T_{I\infty} + G D}{G} = \frac{(b_1 - D) A^3}{((S + \ell)^2 + (b_1 - D)^2)^{3/2}}$$

The unknowns for which we have to solve are S; b_1; A. Since no closed solution can be found, a computer program was the only answer to the problem.

A computer program was developed to this end and it turned out that there are always four valid solutions to the problem. Also, it was found that temperature measuring errors had a great effect on the calculated coordinates of the "obstacle." For the mathematical treatment of the geothermal sources, a realistic model is being developed at the present time.

SECTION 5

EXPERIMENTAL

The Barnes 11-512 Radiometer was delivered to us with several weeks delay. One week of tests was spent on this instrument which showed that the radiometer shifted baseline over periods of between 45 to 60 seconds.

The instrument has been returned to Barnes for repair. It should be returned to us by the end of November, 1971. As soon as the instrument is through its lab shakedown test, arrangements will be made for a field trip to the experimental mine of the Colorado School of Mines.